Topic A3: Indoor air microbiology

INDOOR DAMPNESS AND MOLD AS INDICATORS OF RESPIRATORY HEALTH RISKS, PART 5: COMPARISON OF MOISTURE METERS AND A WATER ACTIVITY SENSOR TO DETERMINE THE DAMPNESS OF GYPSUM WALLBOARD

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SUMMARY

Building dampness has many causes and is among the most pervasive and persistent indoor environmental concerns. A glove box enclosure was evaluated for its suitability as a test environment to determine the moisture content of building materials, gravimetrically and with various field instruments, after conditioning the materials to different humidities using saturated aqueous salt solutions. Gypsum board was chosen as the first test material because of its wide use. At equilibrium conditions, moisture content was measured with two handheld moisture meters that have been used to measure residential dampness in epidemiological studies. Dampness also was tracked with a data-logging moisture transmitter attached to a gypsum board specimen, and water activity was tracked with an attached, data-logging water activity sensor. This paper presents preliminary findings and discusses plans for future work. Five moisture conditions were achieved from 11%–99% relative humidity. The lowest moisture content at which increased health risks have been observed in epidemiological studies was 10%–15% moisture content, which corresponded to ~60%–85% equilibrium relative humidity in the glove box and 0.60–0.85 water activity or ~1%–3% gravimetric moisture content for gypsum board.

INTRODUCTION

In a report on indoor moisture and mold, the U.S. Department of Housing and Urban Development noted that there was no generally accepted definition of dampness or of what constituted a dampness problem nor was there a generally accepted method for measuring residential dampness (HUD, 2005). The World Health Organization has defined dampness as any visible, measurable, or perceived outcome of excess moisture that causes problems in buildings, e.g., mold or mold odor; water leaks or material degradation; or directly measured excess moisture, such as elevated relative humidity (RH, >75%) or high moisture content (MC, unspecified) (WHO, 2009).

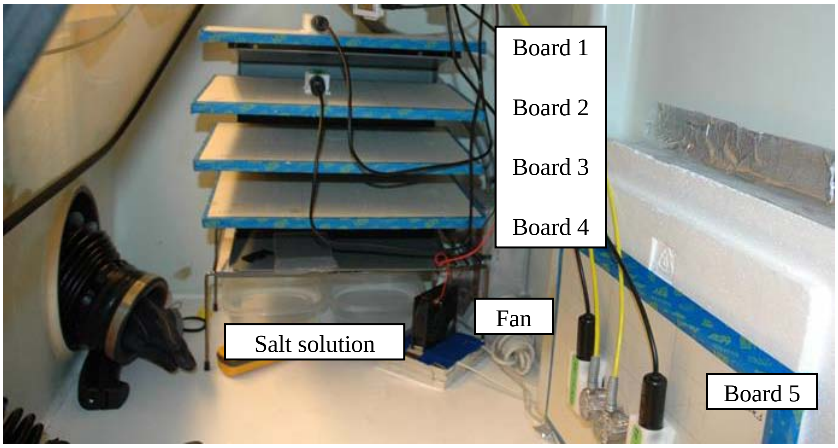
MC describes the amount of water in a material and is usually expressed as a percentage of the mass of the oven-dried material, here referred to as gravimetric moisture content, GMC. MC is a material-specific, relative measurement of a material's dampness, and materials of different densities can have the same MC but hold different amounts of water. MC can be measured in the field in various ways, e.g., with electrical-resistance moisture probes because the resistance of a material decreases with increasing MC (Derome et al., 2001). The moisture meters routinely used in the field are designed primarily to measure the MC of wood, and readings on other materials are reported as percentage wood moisture equivalent (%WME, the theoretical MC that a piece of wood would attain when in moisture equilibrium with the material being measured). Unlike MC, water activity (A_w) is an absolute measurement of dampness that is independent of material and directly relevant to microbial growth. At equilibrium conditions, the A_w of a material equals the relative humidity (RH) of the surrounding air (equilibrium RH, ERH); i.e., A_w = ERH (%)/100; A_w range: 0–1 (unitless); ERH range: 0%–100%. MC measurements are often used to identify water damage to guide remediation, but field measurement and tracking of water activity (A_w) in building materials has not been practical until recently.

This paper describes development of a method to compare the GMC, the MC measured with moisture meters, and the A_w of gypsum board using a glove box enclosure and aqueous salt solutions to achieve different humidity conditions. A related paper describes a one-dimensional simulation of these results conducted using CHAMPS, a Combined Heat, Air Moisture, and Pollutant Simulation program (Chen et al., 2014). This work is part of a multi-component, on-going effort at the Indoor Air Quality Section of the California Department of Public Health to develop evidence to support *quantitative*, health-protective guidelines for indoor dampness and dampness-related agents, whether the agents are microbial, chemical, or other factors as yet unrecognized (Mendell et al., 2014).

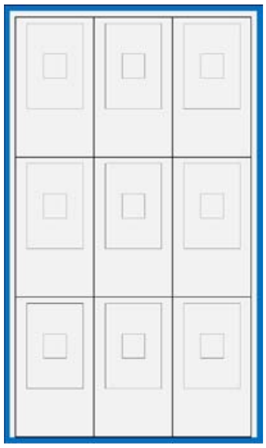
METHODOLOGIES

A sheet of gypsum wallboard was cut into five 23- × 36-cm boards and the edges were smoothed and sealed with masking tape (Gold Bond® Brand, National Gypsum Company, Charlotte, NC). The dry weight of the boards was determined after two weeks in an oven at 40°C (ASTM, 2010). Data-logging A_w sensors were attached to boards 1 and 2 (A_w: Decagon Devices, Inc. Pullman, WA) (Figure 1a). Boards 3 and 4 were left free so that their MC could be determined by measuring their weight increases (GMC) (Figure 1a). Two data-logging A_w sensors and two data-logging, two-pin moisture transmitter electrodes were attached to the fifth board (MT: Model MTC-60 with 2-E/H electrodes, Delmhorst Instrument Co., Towaco, NJ) (Figure 1a). The boards and a balance were placed in a 1.3- × 0.8- × 0.9-m fiberglass glove box (Model 50350, Labconco Corporation, Kansas City, MO) (Figure 1a). Different RH conditions were achieved at 23°C with silica gel desiccant (23% ERH), aqueous salt solutions of K_2CO_3 (42% ERH) and NaCl (71% ERH), and deionized water (86% ERH without a mixing fan and 99% ERH with a fan) (ASTM, 2010 and 2012). The exposed surface area for the aqueous solutions was ~200 cm^2. Humidity in the glove box was measured with an RH and temperature (T) data logger (HOBO: UX100-011; Onset, Cape Cod, MA). Conditions in the glove box took from one to four weeks to reach equilibrium.

When an RH condition in the glove box had been stable for at least 12 hours (i.e., RH and A_w readings did not change more than ±1%), the digital data for the A_w sensors, the moisture transmitters (MT), and the RH/T data logger were downloaded and 12-hour averages were calculated. Boards 3 and 4 were weighed in the glove box, and GMC was determined relative to their original dry weights. MC readings were made at nine locations on boards 1–4 with two handheld moisture meters (Figure 1b): duplicate, pinless meters set for a density (ρ) of 0.5 g cm^{-3}, the manufacturer's recommendation for gypsum board (EP: Electrophysics Model CT100, Ontario, Canada) and duplicate, pin-type moisture meters (PS: Protimeter Surveymaster, GE, Billerica, MA). These meters were chosen because they have been used in studies of environmental exposures and respiratory health (Macher et al., 2014; Mendell et al., 2014; Mendell, 2014). The 12-hour A_w readings for boards 1 and 2 and the 12-hour %WME readings for the two MTs on board 5 were averaged. The GMCs for boards 3 and 4 also were averaged as were the %WME readings from the EP and PS moisture meters for boards 1–4. Calibration data for the moisture meters was obtained from the manufacturers' literature (EP, PS, and MT). The electrical signals for the handheld meters were converted automatically to %WME, but the output for the moisture transmitter required conversion from milliamperes (mA) to %WME using a table provided by the manufacturer.



(1a)



(1b)

Figure 1. (1a) Side view of glove box with five pieces of gypsum board, and (1b) Front view of a board showing nine measurement locations for two handheld moisture meters (grid dimensions equal the footprint of a pin-less moisture meter), the sensing area of this meter (larger boxes at tops of measurement locations), and the area used for moisture measurements with a two-pin meter (smaller boxes at the centers of the larger sensing areas).

RESULTS AND DISCUSSION

No differences were observed between the A_w measured with single sensors on boards 1 and 2 (all sides open to the air in the glove box) and the paired sensors on board 5 (front and sides exposed but back fixed to polystyrene foam attached to the rear wall of the glove box) (Figure 1a). Figure 2a shows the linear relationship (as expected) between the ERH measured in the glove box and the average A_w measured at the surfaces of boards 1 and 2 for five equilibrium conditions. These findings confirm that the air within the small chambers of the A_w sensors attached to boards 1 and 2 was in equilibrium with the RH conditions of the air in the surrounding glove box.

Figure 2b shows the non-linear relationship between the average A_w measurements for boards 1 and 2 and the average gravimetrically determined MC of boards 3 and 4. When the GMC of gypsum board exceeded ~3%, A_w exceeded 0.8 (Figure 2b), the minimum needed for the growth of many microorganisms (Flannigan and Miller, 2011).

The manufacturers of the handheld moisture meters provided tables of expected meter readings for wood but not gypsum board, and the manufacturer of the moisture transmitter provided information for both materials. Figure 3 shows the relationships between wood MC and meter readings for the two handheld meters (EP and PS plotted on the left vertical axis, wood = Douglas fir, $\rho = 0.5$ g cm^{-3}) and the moisture transmitters (MT plotted on the right vertical axis, wood = unspecified) (manufacturers' calibration data). Agreement between the pinless, handheld EP meter (■) and wood MC was perfect because the meter was calibrated (with electronic density compensation) for Douglas fir at a temperature of 20°C (Figure 3). The glove box temperature was 23°C, but no correction is required for temperatures 20°C ±12°C. The lowest wood MC in the EP manufacturer's information was 4%.

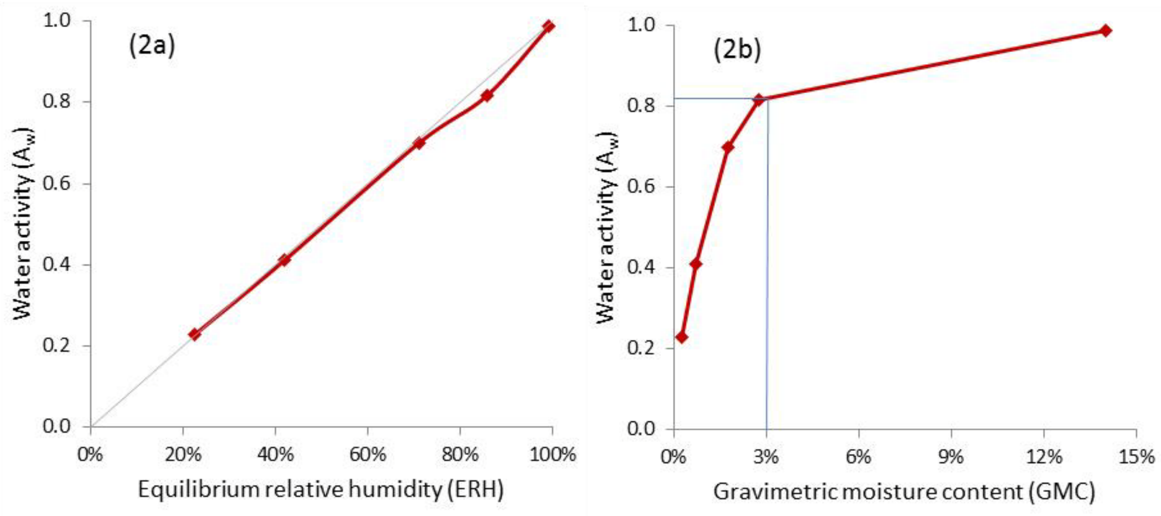


Figure 2. (2a) Water activity (A_w, unitless) of gypsum board at five equilibrium relative humidity (ERH) conditions, and (2b) A_w and corresponding gravimetrically determined moisture content (GMC) of gypsum board at the five ERH conditions in Figure 2a.

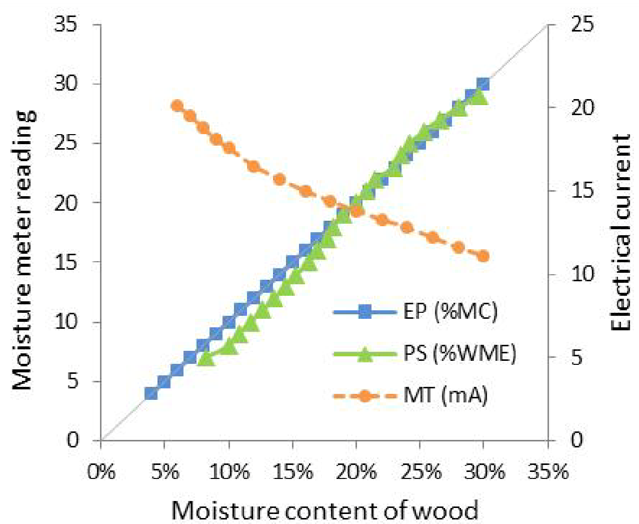


Figure 3. Expected moisture meter readings for wood at different moisture content conditions; handheld meters — EP (■), Electrophysics pinless moisture meter (percentage moisture content, %MC) and PS (▲), Protimeter Surveymaster two-pin moisture meter (percentage wood moisture equivalent, %WME); and the data-logging moisture transmitter — MT (●), Delmhorst two-pin moisture meter (electrical current in units of milliampere, mA).

Agreement between the two-pin, handheld PS meter (▲) and wood MC was linear between ~12% and ~25% WME, but slightly non-linear above and below these levels (Figure 3). This meter also was calibrated for wood at 20°C, but no correction is required for temperatures 20°C ±5°C. The lowest wood MC in the PS manufacturer's information was 8%.

The two-pin moisture transmitter (MT, ●) measured electrical resistance. This is plotted on the second vertical axis in Figure 3, which shows the inverse relationship between MC and resistance. The decline was less steep above 15% wood MC. The lowest wood MC in the MT manufacturer's information was 6%.

There was little difference in measured moisture for the nine measurement locations on boards 1–4 (coefficients of variation: 0%–9% for both the EP and PS meters). Therefore, a smaller board would suffice because dampness was found to be the same on the edges and in the center of a broad at equilibrium conditions. Figure 4 shows the corresponding relationships between the ERH measured in the glove box and the average GMC of boards 3 and 4 as well as the average MC of boards 1–4 as measured with the two handheld moisture meters (duplicate EP and PS meters) and the average MC of board 5 as measured with the moisture transmitters (duplicate MT meters).

In Figure 5, the results in Figure 4 are arranged to show the relationships between gravimetric MC and MC as measured with the three moisture meters.

The pinless EP moisture meter (■) gave readings at all test humidity conditions and corresponded directly with the GMC of gypsum board (Figures 4 and 5), similar to its direct relationship with wood MC (Figure 3). When the humidity was below 80% ERH, both GMC (◊) and EP readings increased approximately linearly with ERH (Figure 4). At higher RH (i.e., ≥90%), the increases were steeper.

Measurements were available for only three ERH conditions for the two pin-type meters, therefore interpretation is tentative. However, these meters appeared to correspond more directly to A_w than to the GMC of the gypsum boards (PS and MT in Figures 2b and 5). The PS meter has been described as measuring only the free water in a material (GE, 1996). Gypsum board has a lower water holding capacity than wood, and the PS meter (▲) was unable to detect dampness in gypsum board when humidity in the glove box was below ~70% ERH (Figure 4), which corresponded to 0.7 A_w or ~2% GMC for the gypsum boards (lowest wood MC: 8% in Figure 3). The moisture transmitter (MT, ●) gave no reading at the lowest humidity condition in the glove box (23% ERH, 0.2 A_w, 0.3% GMC) (Figures 4 and 5) and data for 42% ERH was lost, if measurable, due to failure of the data logger.

The highest GMC we were able to reach through water adsorption from humidified air was 14%, which resulted in moisture meter readings of 34, 23, and 20 %WME for the EP, PS, and MT moisture meters, respectively. Higher meter readings are possible but gypsum board would have to be wetted directly to reach higher GMCs. In future tests, we may wet gypsum board directly by water immersion to reach higher MCs and also determine if previously water-damaged board adsorbs water from air in the same manner as never wet board, as used here.

The lowest MC level at which increased health risks have been observed in epidemiological studies was 10%–15% WME as measured with the PS meter (Mendell, 2014). This range corresponded here to ~60%–85% ERH in the glove box and 0.60–0.85 A_w or ~1%–3% GMC for the gypsum boards. Future plans include increasing the number of RH conditions and continuing to use the mixing fan, which rapidly increased ERH from a constant 86% for water without the fan to 99% with the fan, to shorten the equilibration times. We also shall compare measurements for water desorption as well as for adsorption as reported here, evaluate the performance of the A_w sensor and moisture meters on other representative building materials, and conduct further simulations (Chen et al., 2014).

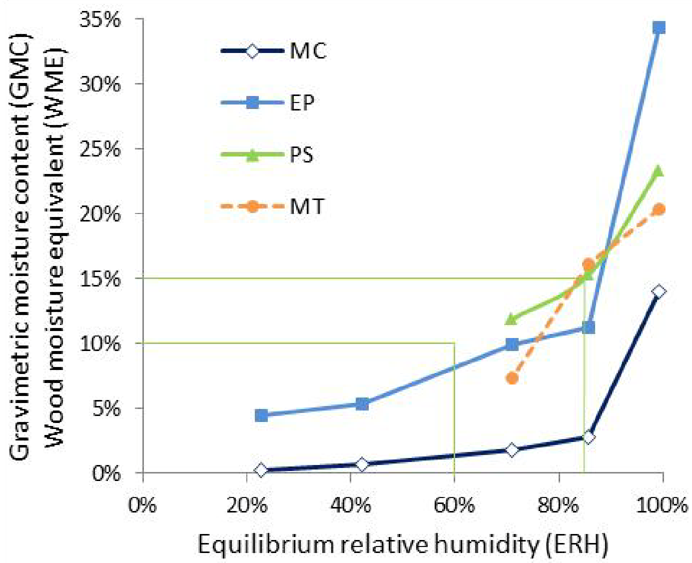


Figure 4. Moisture content (MC) of gypsum board at the five equilibrium relative humidities (ERH) in Figure 2 as determined gravimetrically (plotted as gravimetric moisture content, GMC, ◊) and as measured with moisture meters (plotted as wood moisture equivalent, WME) — EP (■), Electrophysics pinless moisture meter; PS (▲), Protimeter Surveymaster two-pin moisture meter; and MT (●), Delmhorst two-pin moisture transmitter.

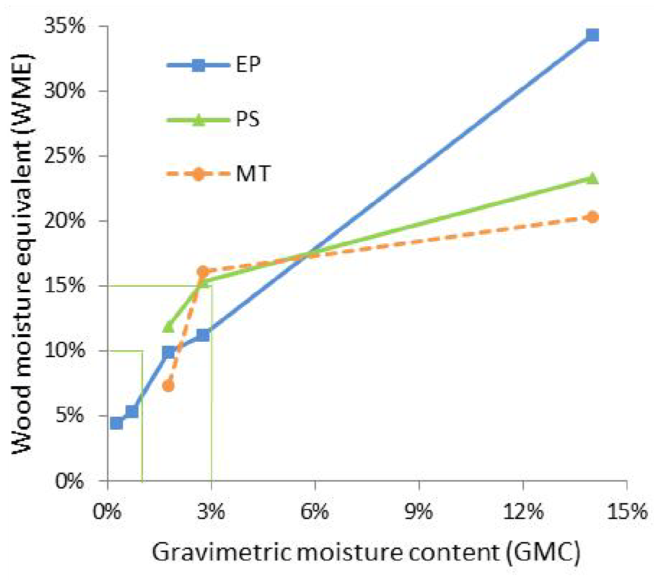


Figure 5. Moisture meter results from Figure 4 at the five gravimetric moisture contents (GMC) that resulted from the five equilibrium relative humidity (ERH) conditions in Figures 2a and 4 — EP (■), Electrophysics pinless moisture meter; PS (▲), Protimeter Surveymaster two-pin moisture meter; and MT (●), Delmhorst two-pin moisture transmitter.

CONCLUSIONS

The glove box and aqueous salt solutions were suitable for the evaluation of moisture meters and water activity sensors to measure the dampness of gypsum wallboard. Water activity (A_w) measurements on gypsum board corresponded directly to humidity conditions in a glove box test chamber (Figure 2a). Two pin-type moisture meters corresponded directly to the humidity conditions and the measured A_w of gypsum board (A_w in Figure 2b and meters PS and MT in Figure 5). A pinless moisture meter corresponded directly to the gravimetrically determined moisture content of gypsum board (EP in Figures 4 and 5).

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